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Ionospheres and Radio Physics 1958-1964

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Foreword

THIS VOLUME IS ONE OF A SERIES which summarize the progress made during the period 1958 through 1964 in discipline areas covered by the Space Science and Applications Program of the United States. In this way, the contribution made by the National Aeronautics and Space Administration is highlighted against the background of overall progress in each discipline. Succeeding issues will document the results from later years.

The initial issue of this series appears in 10 volumes (NASA Special Publications 91 to 100) which describe the achievements in the following areas: Astronomy, Bioscience, Communications and Navigation, Geodesy, Ionospheres and Radio Physics, Meteorology, Particles and Fields, Planetary Atmospheres, Planetology, and Solar Physics.

Although we do not here attempt to name those who have contributed to our program during these first 6 years, both in the experimental and theoretical research and in the analysis, compilation, and reporting of results, nevertheless we wish to acknowledge all the contributions to a very fruitful program in which this country may take justifiable pride.

HOMER E. NEWELL
Associate Administrator for
Space Science and Applications, NASA

Preface

THE IONOSPHERE, an ionized region around the Earth capable of reflecting radio waves, is used regularly in radio communications to guide signals around the curvature of the Earth. It is produced by the action of solar radiation on the Earth's atmosphere, in which process potentially harmful portions of the Sun's X-ray and ultraviolet radiation are absorbed. The ionosphere is thus an important and interesting part of our near-space environment. Similar ionized regions may be expected in other parts of space, but since very little is known about these, this report is confined to the Earth's ionosphere.

Apart from the scientific interest in near space and the practical prospect of improving long-distance radio communications, there is another cogent reason for including ionospheres and radio physics in the space science program. The interaction of radio waves with ionized regions provides a powerful tool for the investigation of their ionization and magnetic fields from great distances. Ionospheric theory and measurements of the radiation flux enable the ionization to be related to the static and dynamic properties of the local medium. This is a fruitful approach to planetary studies, particularly when contamination must be avoided, and to studies of the very hot solar corona. It is axiomatic that these tools and theories must be developed, tested, and applied to our own ionosphere before we can venture further afield with any confidence. Additional requirements come from radio astronomy, where an understanding of the interaction between an ionized medium and a receiving antenna is important to the measurement of low-frequency signals in space and where ionospheric refraction and focusing may be put to good use in increasing antenna directivity.

Prior to the advent of rockets and satellites, the Earth's ionosphere could only be investigated by indirect means, and much ingenuity was expended on deducing the properties of the ionosphere from the changes impressed on an exploring radio wave—a procedure similar to investigating the topography of a rugged terrain by observing the way in which a ball bounces from it. In a situation where neither the neutral atmosphere, nor the ionization, nor the causative solar radiation could be directly observed, it is not surprising to note the highly speculative nature of ionospheric physics before the introduction of more direct methods of *in situ* observation made possible by rockets and satellites.

Progress in understanding the ionosphere is closely related to progress in a number of other areas: solar physics, responsible for investigating the radiation which produces the ionosphere; planetary atmospheres, responsible for defining the neutral atmosphere from which it is formed; and meteorology, through the connection recently discovered with the lower ionosphere.

A necessary prerequisite to understanding the ionosphere is to obtain an adequate description of it. Because of the ionosphere's great variability with both time and position, such a description requires a great deal of data. Until quite recently, these data were essentially limited in geographical coverage to the more populous parts of the globe, and in altitude to below the peak of the F-region (about 300 kilometers). It is a sign of real progress that satellite-borne topside sounders have now obtained data in quantity from above the F-region. The importance of this is made clearer by the realization that there is more than twice as much ionization above the F-region peak than there is below. These data, however, have only been obtained during the recent period of low solar activity, and this work must be continued to at least the next solar maximum to complete the description.

Considerable progress has been made in relating particular portions of the solar spectrum to the ionization produced at different altitudes. Much more work needs to be done, however, before the state of the ionosphere can be computed from a detailed measurement of the incoming solar flux, since the processes of ionization removal are not yet clear and the relative roles of chemical recombination and bodily transport often cannot be distinguished. Indeed, much more work is needed, both on rates of reaction and on the dynamics of the ionosphere.

Unexpectedly, helium was discovered to be an important constituent in the upper atmosphere. Its presence was postulated from a study of satellite drag measurements and firmly established from an investigation of the ionized constituents of the ionosphere. The variations of helium concentration with altitude, latitude, and solar activity are currently under study and have not yet been fully explained.

The development of techniques for measuring both neutral and charged particle temperatures resulted in the discovery that the charged particles, produced by photoionization of the neutral atmosphere, can maintain temperatures in excess of the neutral gas. These investigations have shown that the excess temperature can vary with altitude, season, time of day, and latitude, but have not as yet revealed any seasonal changes. Spaceborne instruments and ground-based backscatter sounders played important roles in this discovery. It remains to be seen whether the existing theories correctly predict the variations with solar activity which should be observed in the next few years.

Intensive work has been done on a phenomenon known as sporadic E. It has been shown that sporadic E is a very thin, intense layer of ionization associated with wind shears in middle latitudes, but is a different phenomenon over the magnetic equator where it is associated with an instability of flow in the intense electrojet current.

A number of new phenomena have been discovered in the interactions between electromagnetic waves and plasmas in the ionosphere. Resonances have been observed at different frequencies associated variously with the Earth's magnetic field, the electron density, and the ionic composition. In addition, an examination of VLF signals received in satellites has resulted in the discovery of several new modes of wave propagation.

In all the items enumerated, the major contributions have come from the use of rockets and satellites supplemented, in some instances, by the incoherent backscatter sounder, which represents the one important new ground-based tool for obtaining data to altitudes of several thousand kilometers at the very few locations where the requisite elaborate installations exist.

Both Soviet Russia and the United States have extensive research programs in ionospheric and radio physics; in the United States, rocket and satellite investigations have been pursued by DOD and NASA. While the U.S.S.R. launched the first satellite and obtained the first high-altitude measurements from rockets, relatively little of this work has received timely publication in any detail. Major contributions have been made by DOD in pioneering work on the solar input during quiet and disturbed conditions and on the absorption of solar radiation as a function of altitude and wavelength. DOD has also made significant contributions in other areas, such as ion composition and wind shear. A substantial portion of the remaining work has been performed through NASA; some of it in-house, some supported by grants and contracts at a number of institutions, and some under international cooperative programs.

This summary was compiled and written by E. R. Schmerling, Physics and Astronomy Programs, Office of Space Science and Applications.

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chapter 1

Introduction

THE EXISTENCE OF IONIZED REGIONS in the upper atmosphere was first postulated in the middle of the 19th century, notably by Gauss (1839, ref. 1) and Balfour Stewart (1878, ref. 2), to account for the small fluctuations in the Earth's magnetic field. This hypothesis was independently revived by Kennelly (1902, ref. 3) and Heaviside (1902, ref. 4) to explain Marconi's feat in 1901 of transmitting radio signals across the Atlantic despite the Earth's curvature. Direct proof of the downward reflection of radio waves from the ionosphere was not obtained until 1925 by Appleton and Barnett (ref. 5). It is interesting to note that about a quarter century elapsed between the electromagnetic field theory of Clerk Maxwell and the establishment of transatlantic radio communications by Marconi, and another quarter century between this achievement and the direct proof of ionospheric reflection by Appleton and Barnett. It is implicit in this report that considerable progress has been made in recent years in reducing substantially the time between major milestones. Because of the ionosphere's importance for radio communications and its inaccessibility to more direct methods of investigation, indirect exploration by radio waves dominated ionospheric research for about a quarter of a century after Appleton and Barnett.

The period from 1946 to 1957 marked the beginnings of rocket exploration. During this time basic techniques were developed that were later combined into increasingly sophisticated payloads. Notable during this period was the realization, largely through the work of Jackson and

Table I.—*Data on NASA-Sponsored Satellites and Space Probes Important in Ionospheres and Radio Physics Research*

(a) Satellites

Satellite	Active life	Apogee, km	Perigee, km	Inclination, deg	Period, min	Items of ionospheric interest
Vanguard III	Sept. 18, 1959, to Dec. 12, 1959.	3 716	512	33	130	Magnetometer coil received whistlers.
Explorer VIII	Nov. 3, 1960, to Dec. 28, 1960.	2 245	419	50	112	Direct measurements by ion traps and electron temperature probes; investigation of vehicle potential; confirmed existence of helium layer in upper atmosphere.
Ariel I	Apr. 26, 1962, to present.	1 176	388	54	101	Electron density capacitance probe; electron temperature gage; ion mass spectrometer; Lyman-alpha gage; first international satellite (U.K.).
Alouette I	Sept. 29, 1962, to present.	1 036	1 000	80	105	Topside sounder; VLF receiver; second international satellite (Canada).
Explorer XVII	Apr. 2, 1963, to July 10, 1963.	740	257	58	95	Ion density; electron temperature and neutral constituents; discovered belt of neutral helium atoms about Earth.
Explorer XVIII (IMP I).	Nov. 26, 1963, to present.	196 982	192	33. 5	3.9 days	Retarding potential analyzer 0–15 eV.
Ariel II	Mar. 27, 1964, to present.	1 288	290	51. 7	101	Galactic radio noise receivers.

Explorer XX	Aug. 25, 1964, to present.	1 020	869	80	105	Fixed frequency sounder; ion mass spectrometer.
Explorer XXII	Oct. 10, 1964, to present.	1 080	889	80	104	Ionosphere beacon; Langmuir probe.
Syncom III	Aug. 19, 1964, to present.	35 799	35 790	....	Synchronous	136-Mc/sec telemetry from antenna fixed in space.
OGO I	Sept. 5, 1964, to present.	148 000	1 800	32	64 hr	Ion and electron trap (spherical and planar); radio propagation: VLF receiver; rf ion spectrometer.

(b) Probes

Probes	Launch date	Apparatus of ionospheric interest	Remarks
ST 2	Oct. 4, 1960	Ion trap	Ion density observed to about 5000 km; He^{+} shown as important constituent from altitude variation.
P 21	Oct. 19, 1961	rf probe, cw propagation	Electron density obtained to about 4000 km.
P 21a	Mar. 29, 1962	cw propagation, rf probe, ion traps	Nighttime high-altitude ionosphere investigation.

Seddon (1958, ref. 6), that the traditional ionospheric layers are not, in general, well separated as had been supposed, but merge gradually into one another, forming a single profile of ionization density with only shallow valleys and gentle peaks.

Another new era began with the launching of Sputnik I in October 1957 and the creation of NASA in 1958. This period marked not only the dawn of the satellite era but also the coming of age of rocket exploration. The experience of small groups of experimenters was pooled, and larger teams, with increasing support, began to put together increasingly complex payloads for the simultaneous measurement of different, but physically related, quantities. A list of the NASA-sponsored satellites and space probes important in ionospheres and radio physics research is given in table I. The year 1958 also saw the beginning of NASA's university and international programs, which made a broad base of technology available to scientists with expert knowledge of their own fields but with limited technological resources.

This report attempts to outline the major areas of progress in ionospheric research over the years 1958 to 1964. It deals primarily with the plasma properties of the ionosphere, since the neutral atmosphere, the chemistry of the atmosphere, and the Sun as a source of ionizing radiation are discussed in separate reports. Particular emphasis has been given to the topside of the F-region, about which little was known before 1958. No attempt has been made to cover storm and other disturbance phenomena, since relatively little progress has been made in these areas. Drastic selection was necessary in a report of this large scope but small size, and topics and references which might otherwise have been included had to be omitted.

chapter 2

The Ionospheric Regions

THE COLLISION-DOMINATED REGION

THE D-REGION IS USUALLY CONSIDERED the lowest portion of the ionosphere, and ranges in altitude from about 50 to 85 kilometers. The lower part of this range is sometimes called the C-region because of its cosmic ray origin. Below 50 kilometers is a region where ions exist in the form of clusters. In the D-region the motion of electrons is dominated by collisions with neutral particles, thus causing most of the radio-wave absorption to occur here. This absorption provides a powerful tool for making measurements. Too high for balloons and too low for satellites, the D-region is investigated by the transmission of radio waves through it, from the ground or from above, and by direct-measurement devices carried on rockets. The low density of charged particles, the high neutral density, and the high probability of negative ion formation account for the difficulties experienced in both theoretical and experimental investigations of this region.

Electron density measurements may be made from the ground by a number of techniques. The partial-reflection method of Gardner and Pawsey first reported in 1953 (ref. 7) has been used recently by some workers, but requires great care in its execution and interpretation. The wave-interaction method depends on both electron density and collision frequency. By using pulses, Fejer and Vice (ref. 8) succeeded in improving the height resolution; and by measuring both the phase and amplitude of the interaction, Weisbrod, Ferraro, and Lee (ref. 9) can, in principle, obtain collision frequency and electron density independently. The height resolution is, however, an order of magnitude poorer than can be readily obtained from rockets. The riometer technique of Little and Leinbach (ref. 10) measures the absorption of incoming cosmic noise and is capable of providing coarse electron-density profiles over a limited height range. It is particularly useful during disturbed conditions (ref. 11). The more traditional radio methods based on measuring signals received from low-frequency transmitters all suffer from the disadvantage that they provide integrated information over the transmission path which is difficult to interpret, but these methods can be useful for checking profiles and for monitoring.

The use of sounding rockets brought a tremendous advance in observational techniques, since the integrated properties measurable by radio-propagation methods can produce accurate profiles when these integrals are obtained as functions of known rocket altitudes. The Faraday rotation and differential absorption methods, first described in 1958 by Jackson and Seddon (ref. 6) and Seddon (ref. 12), are particularly suitable for investigating this region and have provided the most reliable results. An interesting refinement of these techniques has recently been described by Knoebel and Skaperdas (ref. 13). In this version, a receiver in the rocket is used in a servo loop to control the power of the extraordinary wave emitted by a transmitter on the ground so that the rocket always sees a constant ratio of ordinary to extraordinary signal. This method insures a large dynamic range and places the simplest portion of the experiment in the rocket.

Apart from the discovery that the traditional ionospheric layers are not well separated, two other important features emerged from the early rocket experiments on radio propagation. Jackson and Seddon proved experimentally that the Lorentz term should not be used in the magnetoionic theory. In addition, Kane (ref. 14) showed that at low altitudes the Appleton-Hartree electron collision frequency must be replaced by an energy dependent electron collision term as discussed by Sen and Wyller (ref. 15).

Among the techniques for making direct measurements of electron and ion density in the collision-dominated region are the Gerdien condenser (ref. 16), the impedance probe (refs. 17 and 18), the Langmuir probe in the conductivity mode (ref. 19), and the spherical electrostatic analyzer (ref. 20). Since the interpretation of data from these instruments presents difficulties, their reliability must at present be placed below that of the radio-propagation technique. The latter is unaffected by sheath, rocket potential, and photoemission effects.

Although there is not yet full agreement on the formation of this region, it seems probable that below 70 kilometers the ionization is produced mostly by cosmic rays, and between 70 and 85 kilometers by Lyman-alpha (1216 Å) ionizing nitric oxide (NO), as discussed by Nicolet and Aikin (ref. 21). Further evidence for this view has been recently adduced by Aikin, Kane, and Troim (ref. 22). Direct verification of this theory is difficult, as the concentration of NO calculated for this process is well below the detection limit of existing mass spectrometers. Barth (ref. 23), however, examining the dayglow spectrum in the 1500- to 3200-Å range from a rocket, has succeeded in detecting NO and measuring its concentration. Further work is proceeding on these important new measurements which have created the fresh problem of accounting for NO concentrations several orders of magnitude greater than required by the Nicolet and Aikin theory. There is also a lesser contribution from X-rays in the range 2 to 8 Å, which can increase with sunspot activity (ref. 24) and is certainly responsible for the enhanced ionization due to

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solar flares which result in radio-communication blackouts (sudden ionospheric disturbances (SID)) in the sunlit hemisphere in medium latitudes. The Lyman-alpha flux remains relatively constant within the limits 3 to 6 ergs/cm^2/sec, while the X-ray flux can vary by several orders of magnitude, according to data from a number of rocket flights and the Greb, Ariel, and OSO satellites. (See, for example, refs. 25 and 26.)

Other D-region disturbances are characterized by an unusually high absorption of radio waves. It has been shown by Bailey (ref. 27) and Webber (ref. 28) that polar cap absorption events (PCA) are due to solar protons. Some disturbances are also associated with aurorae, and days of high absorption are occasionally found in winter at medium latitudes. Aikin, Kane, and Troim (ref. 22) have suggested that the latter may be related to changes of mesospheric pressure, which affects the collision frequency. The evidence found by Bossolasco and Elena (ref. 29) and Aikin, Kane, and Troim (ref. 22) for such a variation of collision frequency with mesospheric pressure requires further verification; however, this effect appears to be an important new result that must be considered in the interpretation of radio measurements currently based on constant-collision-frequency models.

THE PHOTOEQUILIBRIUM REGION

During the day, there is in this region an approximate equilibrium between the process of ion production and loss. This region extends from about 85 kilometers to somewhat above 200 kilometers, including the E and F1, as well as the lower part of the F2, layers. The density of the neutral atmosphere here is sufficiently low to reduce the collision frequency between electrons and neutral particles to such an extent that there is little absorption of radio energy; thus refraction and reflection are the dominant effects on radio waves.

This region may be explored by means of ionosondes, and the work of Budden (ref. 30) and Jackson (ref. 31) led the way for modern methods of obtaining electron-density profiles from ionograms. Although useful for the daytime F-region, these methods do not always show enough detail in the E-region and can produce considerable errors at night from underlying ionization. The incoherent back-scatter technique, first suggested by Gordon in 1958 (ref. 32) and first implemented by Bowles (ref. 33), can give data from about 100 kilometers upward when using 50 Mc/sec near the magnetic equator, and also at lower altitudes when using higher frequencies at other latitudes. The amplitude and spectral distribution of the returned signal can provide information on electron densities, electron and ion temperatures, and ionic composition. These parameters are often difficult to separate, but Moorcroft (ref. 34) discusses how this may be done.

Rocket- and satellite-borne techniques for measuring electron and ion densities and temperatures include cw propagation (Faraday rotation and dispersive Doppler modes (ref. 6)), and a variety of Langmuir probes, ion traps, and antenna impedance devices.

The daytime E-layer has a peak electron density near 110 kilometers (Robinson, 1959, ref. 35) and is the most regular of the ionospheric layers, being only slightly perturbed by tidal effects. It is produced by the action of Lyman-beta (1026 Å) radiation on O_2 and, to a lesser extent, by soft X-rays in the 10-Å to 170-Å range, acting on all the neutral constituents (refs. 36 and 37). Mass spectrometer measurements show that the main ionic constituents below 200 kilometers are NO^+ and O_2^+. At higher altitudes, the F-region is formed by radiation in the 170- to 900-Å range acting principally on atomic oxygen (refs. 36 and 37), and the main ionic constituent becomes

O^+. The conclusion reached in 1956 by Ratcliffe, Schmerling, Setty, and Thomas (ref. 38), on indirect evidence, that the electron density peak is well above the electron production peak has been strikingly confirmed by experiment. Figure 1 shows the electron densities measured in 1961 by Bauer and Jackson (ref. 39) and the photoionization rates obtained by Hinteregger and Watanabe (ref. 37). Although not taken at the same time, these measurements were taken under comparable conditions and show clearly a rising electron density above 200 kilometers caused by a recombination rate that decreases more rapidly with height than the photoionization rate. Ratcliffe, Schmerling, Setty, and Thomas (ref. 38) averaged over seasons and obtained an exponentially decreasing electron loss rate with a value of 1×10^{-4}/sec at 300 kilo-

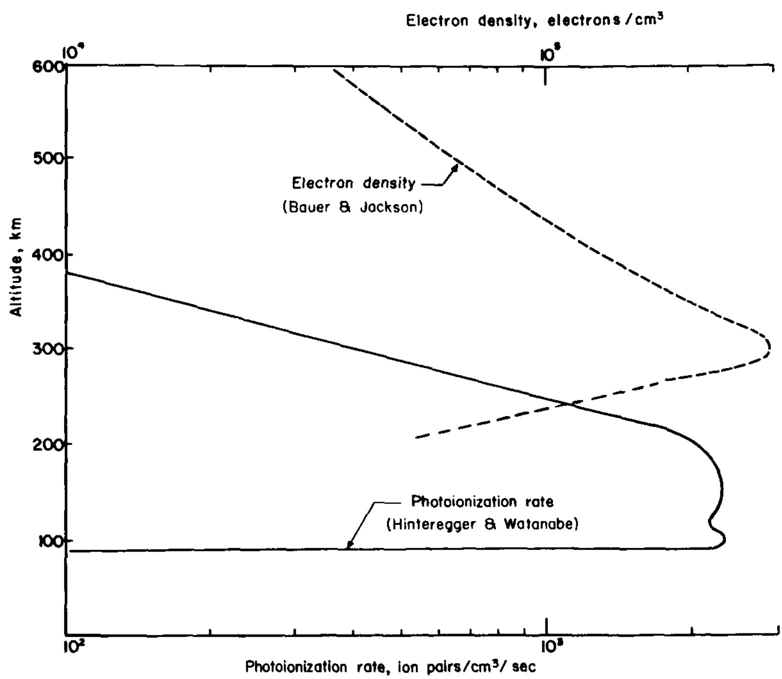


Figure 1.—Electron density (ref. 39) and photoionization rate (ref. 37) as functions of altitude.

meters. The loss rate at night has recently been reexamined by Nisbet and Quinn (refs. 40 and 41) by considering the loss of electrons within a tube of force. They find a loss rate which varies with temperature and with season between 0.2 and 2.0×10^{-4}/sec at 300 kilometers. Their results imply a seasonal change of composition which might have an important bearing on the seasonal anomaly in the F-region.

One of the more striking recent discoveries is the marked difference between electron, ion, and neutral temperatures. Measurements of this disparity from rockets have been reported by Aono, Hirao, and Miyazaki (ref. 42), using resonance methods and Langmuir probes, and by Brace, Spencer, and Carignan (ref. 43) and Nagy, Brace, Carignan, and Kanal (ref. 44), using Langmuir probes. Similar results from backscatter and satellite experiments have been obtained but are more pertinent to higher altitudes. Figure 2 shows the measured electron temperature (T_e) for a quiet day at midlatitudes in midafternoon compared with the neutral gas temperature (T_g), according to Harris and Priester, and measured values of nitrogen temperature (T_{N_2}). The first theoretical attempt to compute electron temperatures by examining energy loss mechanisms for photoelectrons was made in 1961 by Hanson and Johnson (ref. 45). Revisions made by Hanson (ref. 46) and Dalgarno, McElroy, and Moffet (ref. 47) seem to be in general accord with the observations below 350 kilometers.

The diurnal, seasonal, and latitudinal changes of electron density in the E-layer (near 100 kilometers) follow quite closely the dependence on solar zenith angle first deduced for a simple ionospheric layer in 1931 by Chapman (refs. 48 and 49). At higher altitudes, however, marked deviations from this simple behavior occur, and numerous such "anomalies" have been named. Figures 3 and 4 show typical sets of curves illustrating the average diurnal variations of electron density at fixed heights over Huan-

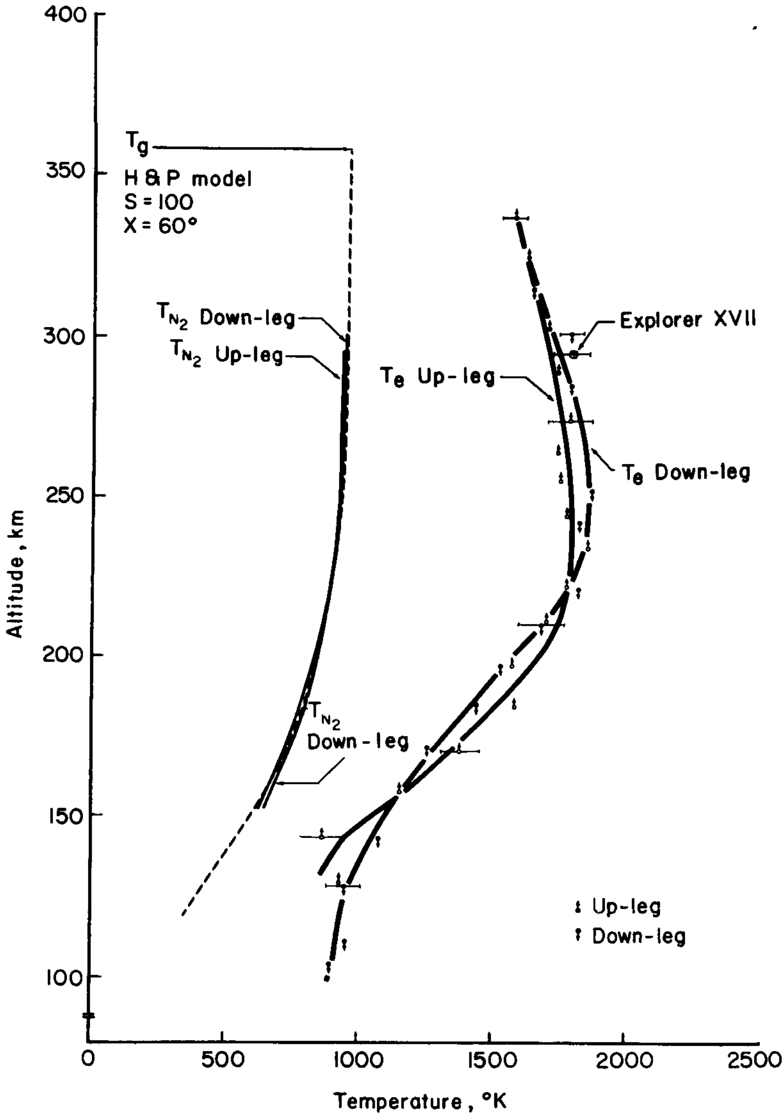


Figure 2.—Measured electron temperature (T_e), measured N_2 temperature (T_{N_2}), and neutral temperature (T_g) computed from the Harris and Priester model. Wallops Island, April 18, 1963, 1604 e.s.t., $\chi=60°$, undisturbed conditions.

cayo, Peru, and Washington, D.C., for April 1958 (Schmerling, ref. 50). A rather large maximum occurs

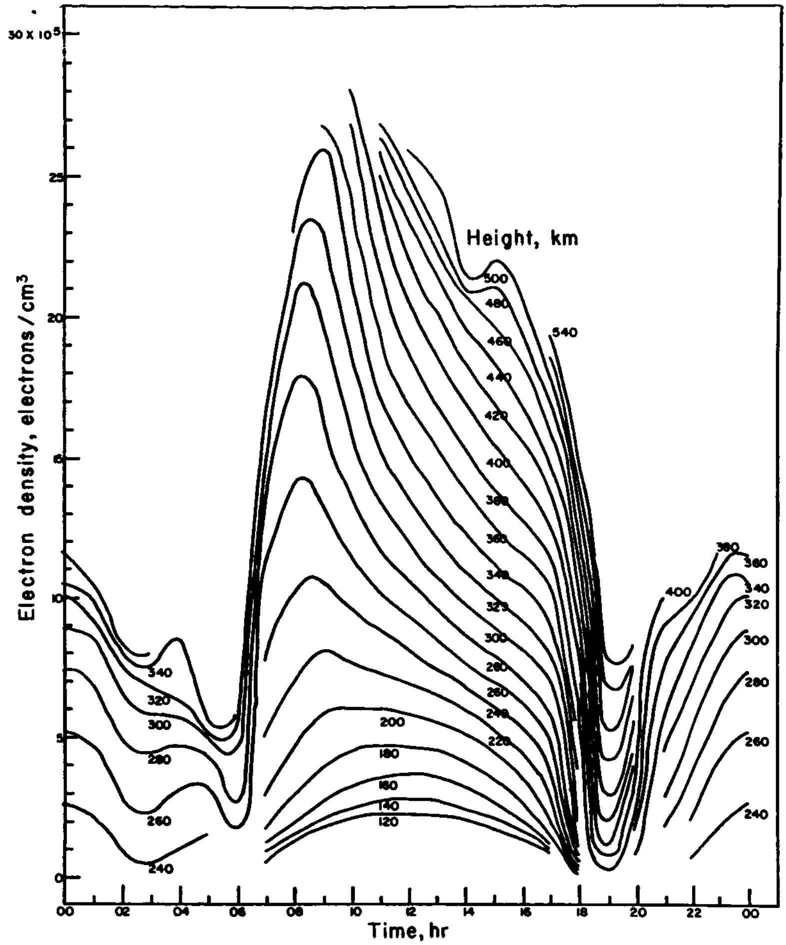


Figure 3.—Average diurnal variations of electron density at fixed altitudes for Huancayo, Peru, April 1958.

well before noon, despite the fact that a simple isothermal theory necessarily predicts a maximum after noon. The higher electron densities over Huancayo (on the magnetic equator) and the more exaggerated form of the anomaly when compared with Washington (at medium latitude) are also to be noted.

There is currently no comprehensive theory of the F-region which can account satisfactorily for the diurnal,

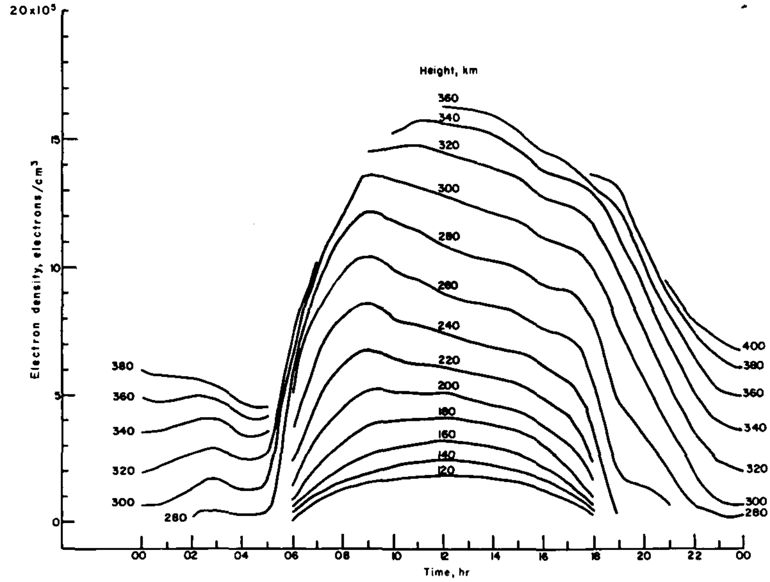


Figure 4.—Average diurnal variations of electron density at fixed altitudes for Washington, D.C., April 1958.

seasonal, and latitudinal changes observed. Only quite recently have attempts been made to incorporate the known diurnal temperature changes of the neutral atmosphere into theoretical models. Norton and Van Zandt (ref. 51), restricting themselves to the daytime equatorial F-layer, were able to generate curves similar to figure 3; and Rishbeth (ref. 52) obtained curves similar to figure 4 for medium latitudes. Discrepancies still exist between laboratory measurements of reaction rates and those required by the above theories, as well as the values needed to account for day and night behavior.

Another striking feature of the electron density distribution is the geomagnetic control, which increases with altitude to the F2 peak. This geomagnetic control has been examined in detail by Croom, Robbins, and Thomas (ref. 53). The nearly symmetrical behavior at equinox noon is shown in figure 5. Although attempts have been made

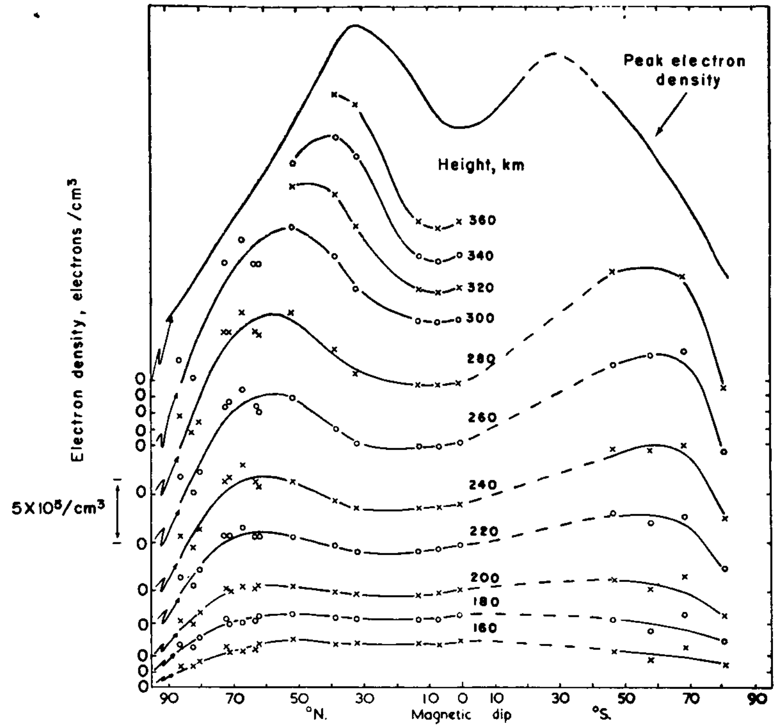


Figure 5.—Noon values of electron density at fixed altitudes as functions of magnetic dip, September 1957. Curves are displaced for clarity. The zero point for each curve is indicated by the figure in the left margin. The scale is the same for all curves.

to account for this distribution by the action of ambipolar diffusion and/or electromagnetic drifts, none of these has yet been free of arbitrary assumptions.

Above the photoequilibrium region, the neutral density decreases sufficiently for plasma diffusion to become important. The F2 electron peak marks the transition between the photoequilibrium region below and the diffusion region above. This transition represents a delicate balance between the competing processes of electron production, recombination, and diffusion; and many effects perturb markedly the height and electron density of the F2 peak.

Although many attempts have been made to account theoretically for the diurnal, seasonal, and geographical variations of electron density around the F2 peak, no really satisfactory theory is currently available.

THE DIFFUSION-DOMINATED (TOPSIDE) REGION

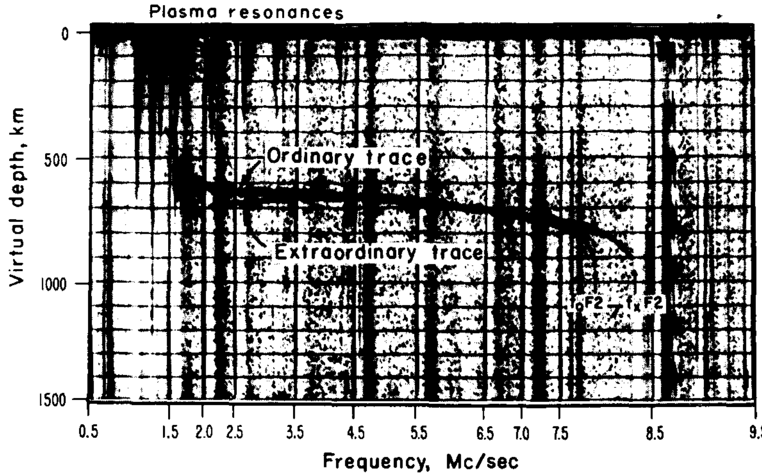
Above the F2 electron peak, the vertical distribution of ionization is influenced mainly by diffusion processes rather than electron production and loss, and the vertical gradient of electron density is more easily accounted for than its magnitude, since the former is given approximately by the hydrostatic-electrostatic equation while the latter is the solution of a complicated boundary-value problem.

The first accepted measurement in this region was made by Gringauz from a Russian stabilized rocket (ref. 54) using a cw propagation technique. Since then, there have been many rocket flights with propagation experiments and a variety of direct measurement techniques based on Langmuir probes and antenna impedance measurements.

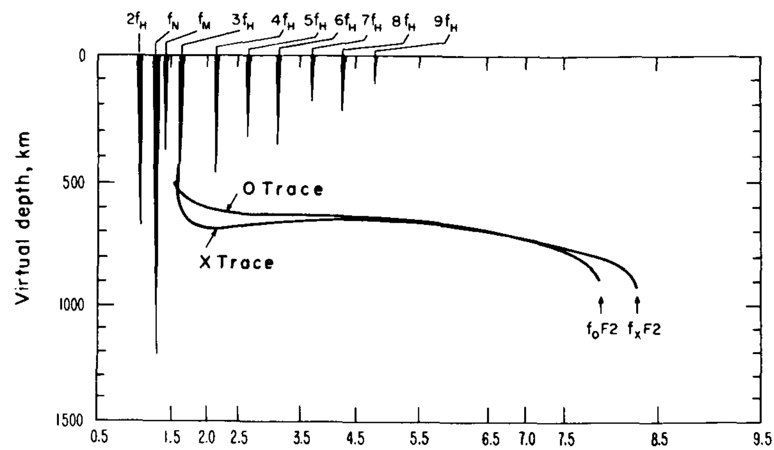
The first satellite measurements were made on the refraction of radio signals (radio rise and radio set) and on Faraday rotation and Doppler dispersion. These techniques are discussed in some detail by Garriott and Bracewell (ref. 55). A more accurate combined Faraday-Doppler (hybrid) method has been devised by Garriott and deMendonça (ref. 56), and second-order refraction corrections have been discussed by Ross (ref. 57). Basically, these observations provide the integrated electron density (electron content) between the ground and satellite and can give information on horizontal gradients and ionospheric irregularities. This type of experiment has two interesting variations. In the first, the transmitter is mounted on a spacecraft with a highly eccentric orbit so that a nearly vertical altitude scan is obtained over part of the orbit, as is being done with OGO I (formerly OGO A) by Lawrence and Garriott (as reported by Schmerling (in ref. 58). In the second, a synchronous (geostationary) satellite is used so that the diurnal variation may be observed in detail without the drastic averaging needed with other orbits (ref. 59). Important differences have already been found between the electron content variations at different latitudes, thus suggesting a latitudinal change in the ratio of ionizing to recombining constituents. A more elaborate multifrequency experiment capable of measuring group and phase-path differences as well as Faraday rotation would enable the F-region electron content to be separated from the protonospheric electron content by the different (magnetic) weighting in the electron contents obtained by these methods. Such an experiment is currently under consideration.

The incoherent backscatter technique, which was discussed in connection with the photoequilibrium region, is a powerful new tool capable of making nearly continuous observations, but rather elaborate facilities are needed. Recent developments in spectral analysis of the returned signal and combined use of backscatter measurements with topside sounder and rocket profiles will probably lead to significant advances in separating the effects of electron density, electron and ion temperatures, and ionic mass.

The plasma resonances, first reported in 1961 on a rocket flight by Knecht, Van Zandt, and Russell (ref. 60) and since observed regularly by Alouette I and Explorer XX, have revived interest in the physics of plasma oscillations and have provided a valuable tool for measuring both the magnetic field and the electron density around satellites. Three types of resonance are found: at multiples of the electron gyrofrequency, f_H; at the electron plasma frequency, f_N; and at the upper hybrid frequency, $f_M=\sqrt{f_H^2+f_N^2}$. These resonances are excited by energy from the transmitter and are detected by a receiver. Fejer and Calvert (ref. 61) have explained them in terms of electrostatic oscillations and can account for the main



(a) Topside ionogram showing plasma resonances.



(b) Diagrammatic sketch from the ionogram.

Figure 6.—A topside ionogram and diagrammatic sketch from Alouette I showing plasma resonances.

features of the observations. Figures 6(a) and 6(b) show an actual Alouette I ionogram and a labeled interpretation, respectively.

The lower hybrid resonance, reported by Brice and Smith (ref. 62), represents a different type of plasma resonance. This lies between the electron and proton gyrofrequencies, defines a cutoff frequency for propagation transverse to the Earth's magnetic field, and is observed as a sharp lower edge on a band of noise seen by a passive receiver in the 2- to 10-kc/sec range. Unlike the other resonances, separate excitation from a local transmitter does not seem to be needed. This resonance is likely to prove important because the frequency depends on an effective ion mass in the vicinity of the satellite; thus an independently measured parameter is available.

By far the most prolific source of electron density information to date has been the swept-frequency topside sounder of the Canadian-U.S. satellite Alouette I, launched in September 1962. Not only has this sounder produced over 10^6 electron density profile records from above the F2 electron peak, where only a handful had previously been available, but it has actually provided much more detail on the topside than has been obtained on the bottom side from all experiments put together. The sounder sweeps from 0.5 to 11.5 Mc/sec every 18 seconds at an altitude of 1000 kilometers, and a profile can be obtained every 120 kilometers on its trajectory, or approximately every degree of latitude. The ionograms are similar to ground-based ionograms, and their reduction to electron density profiles is also similar, with two important differences. First, the plasma frequency at the equipment is finite and must be determined. Fortunately, the plasma resonances afford a solution to this problem. Second, allowance must be made for the variation of the Earth's magnetic field with altitude. This only requires a refinement in the computations, but must be done with care to avoid significant errors in the deduced vertical gradients used for evaluating the important physical parameters of the topside. There are still some unsolved problems in deducing these profiles from the ionograms, as on a number of occasions the bottomside and topside profiles do not match properly (e.g., ref. 63). However, on the few more elaborately instrumented tests, using simultaneous rocket and backscatter measurements, no serious discrepancies have emerged (ref. 63). Figure 7 shows such a comparison of topside electron density profiles deduced from each of the following: Alouette I, a backscatter sounder, and a rocket probe which contained two independent experiments and was fired close to the satellite. It may be seen that on this occasion good agreement was obtained, but further work is needed to account for the discrepancies observed at other times between topside and bottomside soundings.

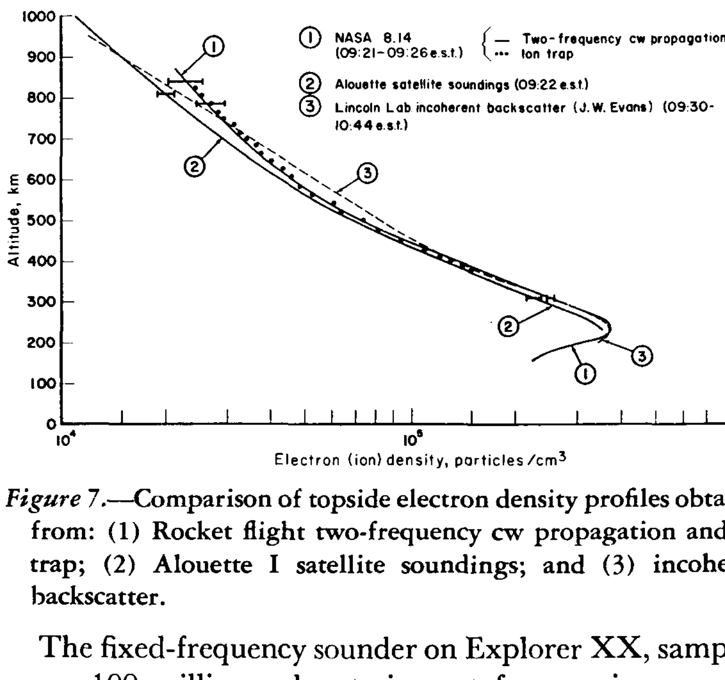


Figure 7.—Comparison of topside electron density profiles obtained from: (1) Rocket flight two-frequency cw propagation and ion trap; (2) Alouette I satellite soundings; and (3) incoherent backscatter.

The fixed-frequency sounder on Explorer XX, sampling every 100 milliseconds, at six spot frequencies, provides much better horizontal resolution of irregularities and plasma resonant structure but much coarser vertical profile data (ref. 64).

Topside Morphology

As revealed by Alouette I, the topside can be roughly divided into three regions: (1) from the magnetic Equator to a dip angle of roughly 30°, where geomagnetic control is very strong; (2) from about 30° to 70° of dip, where the spatial variation is smooth and regular; and (3) above about 70° of magnetic dip, where the spatial distribution shows marked irregularities. The strong geomagnetic control is illustrated in figure 8, which shows electron density as a function of magnetic dip for a number of fixed altitudes on October 3, 1962, taken somewhat before local noon over Singapore. The tendency for the maxima to follow a magnetic field line is easily seen. The development of this structure for different local times along the 75° W meridian is shown in more detail by Lockwood and Nelms (ref. 65). An example of a nighttime distribution on February 17, 1963, is given in figure 9. No adequate treatment of the time-dependent behavior of this distribu-

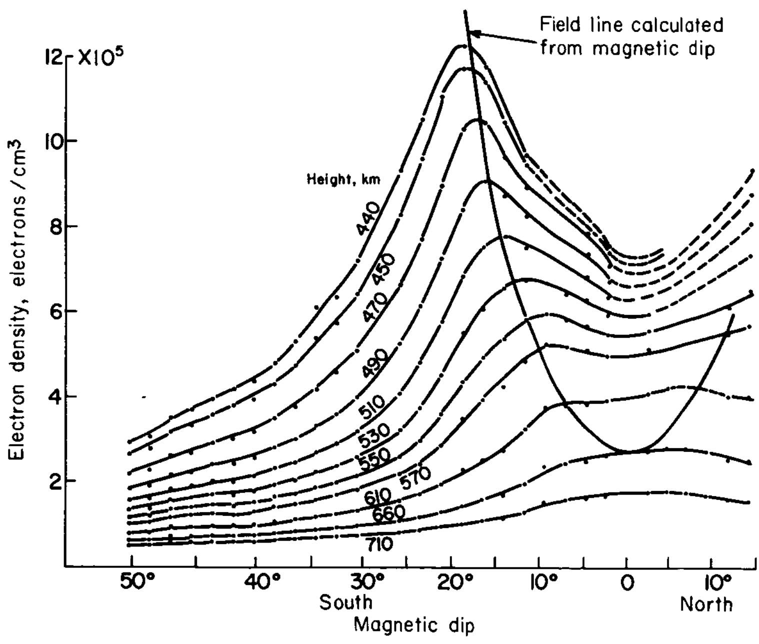


Figure 8.—Topside electron densities at fixed altitudes taken in the late morning on October 3, 1962.

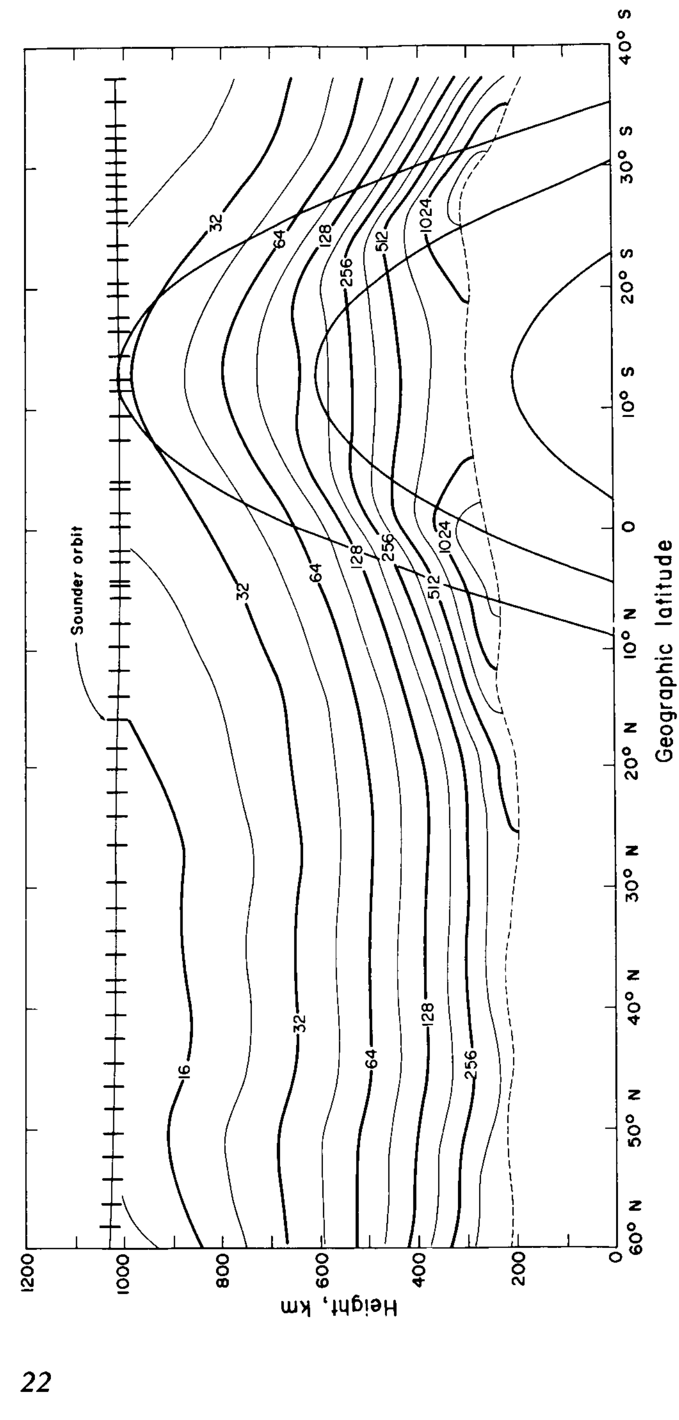


Figure 9.—Contours of fixed electron density ($\times 10^{-3}/cm^3$) as function of latitude; night of February 17, 1963, 81°–65° W.

tion exists, but quite an extensive literature on the steady-state distribution is available. The effect of diffusion in modifying the equatorial vertical profiles into a reasonable approximation of the observed distribution has been discussed by Goldberg, Kendall, and Schmerling (ref. 66), and computations which include the effects of electrodynamic drift terms have been presented most recently by Bramley and Peart (ref. 67) and Baxter (ref. 68). Unfortunately, although the effects of an assumed electrodynamic drift can be computed, probably quite accurately, there is at present neither a satisfactory theory for predicting what this drift should be nor a satisfactory method for measuring it experimentally.

Field-alined strata (Sayers, ref. 69) and ledges in the electron density profiles (King, et al., ref. 70) are common features. Figure 10 shows an Alouette I ionogram, with cusps in both ordinary and extraordinary traces near 2.5 Mc/sec, indicative of a ledge. The corresponding electron density profile is shown in figure 11. Since the ledge is less prominent on the profile, it may be more precisely defined by taking as coordinates the plasma frequency of the cusps and the true height corresponding to this plasma frequency. Figure 12 shows the alinement of these ledge coordinates, represented by dots, along a magnetic field line.

The existence of these field-alined structures and the ducted propagation effects seen on Explorer XX can be considered evidence of the magnetic guidance that permits ionization to move along, but not across, field lines. Attempting to interpret the slopes of the profiles, King (ref. 70) suggested that they should be measured along field lines rather than vertically. Preliminary results obtained in this way seem to be more nearly in accord with independently obtained temperature and composition data.

Although the latitude variation is currently quite well established (for the minimum phase of the solar cycle), the

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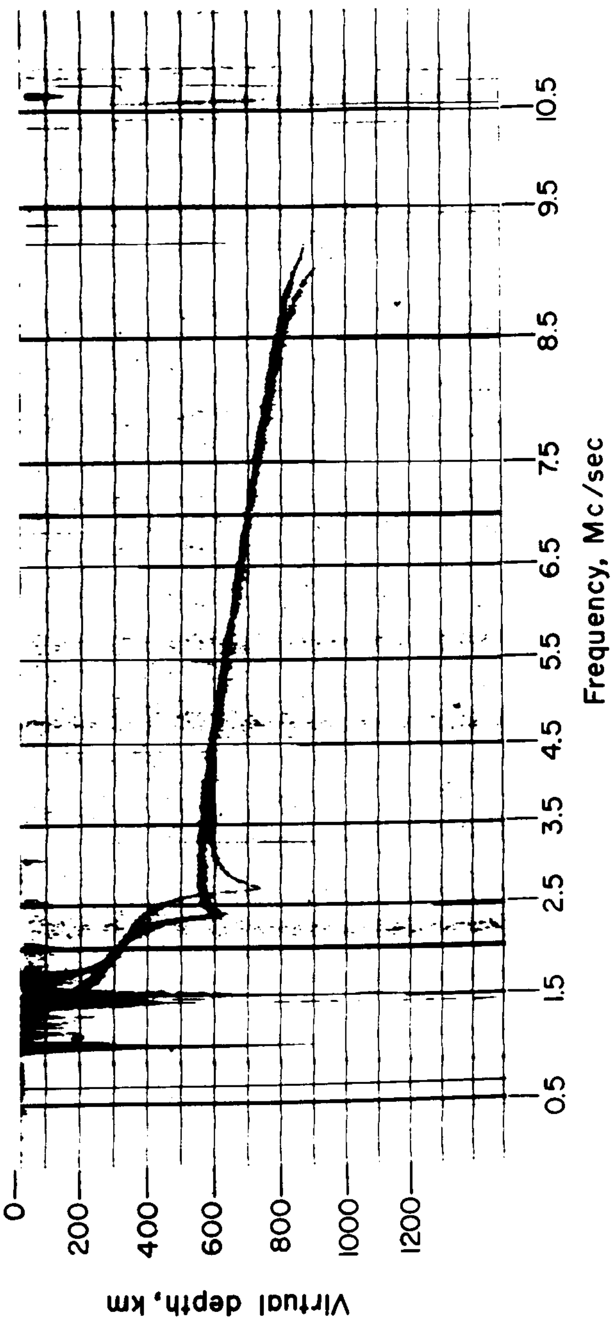

Figure 10.—Alouette I ionogram, with cusps indicative of a ledge. October 21, 1962, 00:39 G.m.t., 72° W, 11° S. Satellite height = 1018 kilometers.

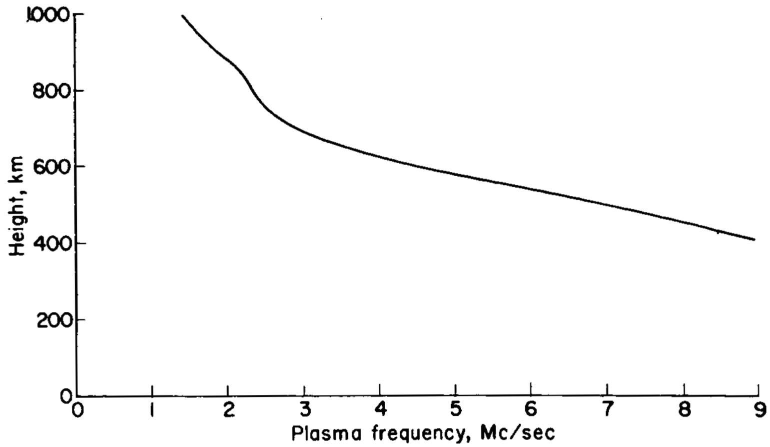

Figure 11.—Profile corresponding to ionogram in figure 10.

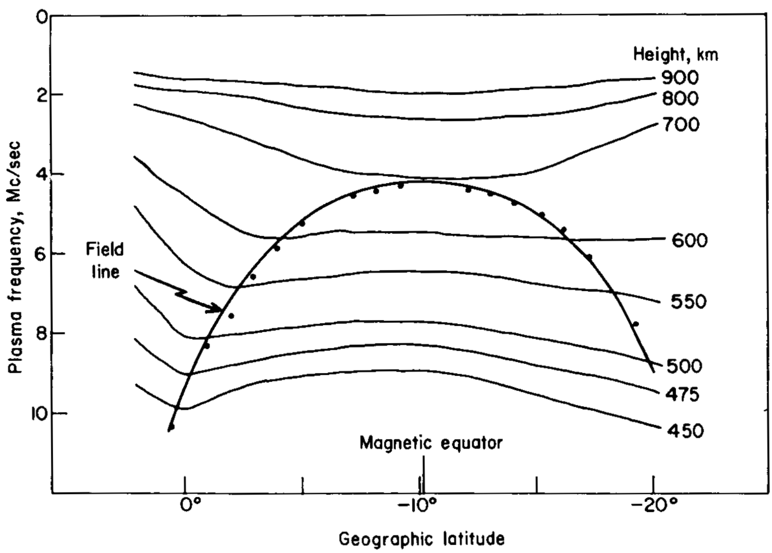

Figure 12.—Plasma frequency contours with dots to show ledge coordinates. November 2, 1962, 1800 l.m.t., 88.7° W.

diurnal variation is not known nearly as well, since the slow precession of the Alouette I orbit necessitates averaging over several months, and the F-region exhibits considerable day-to-day variability. Some data for the period from October to December 1962 have been presented by Bauer and Blumle (ref. 71). Figures 13 and 14 show these curves for latitude ranges 35° to 40° N and 40° to 45° N, respectively.

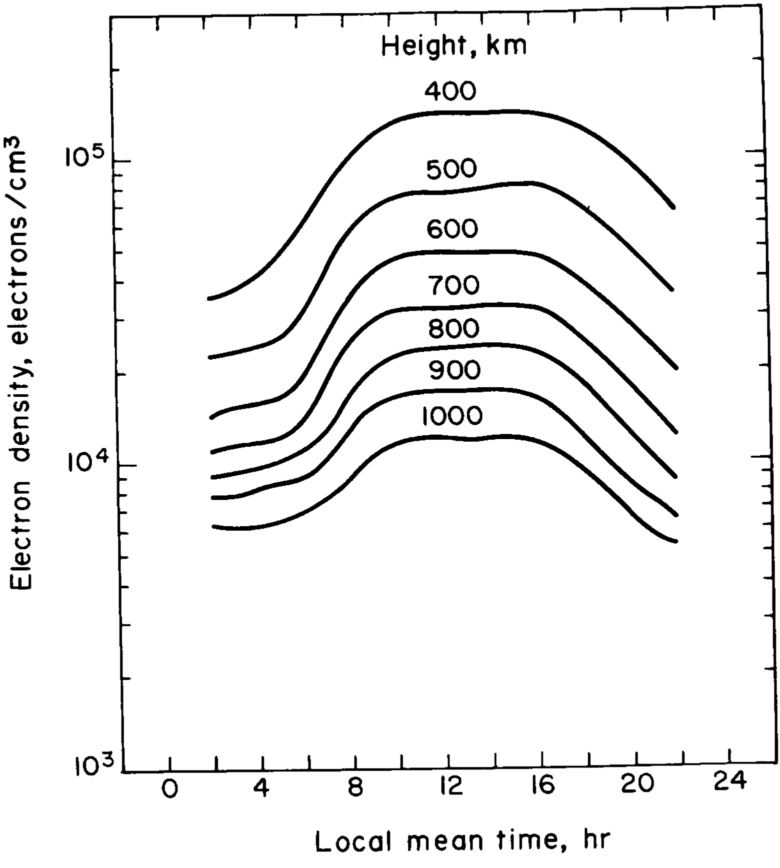

Figure 13.—Average diurnal variation of electron density at fixed altitudes: 35° N to 40° N, October–December 1962.

Topside Composition

Immediately above the F2 electron peak, the chief ionic constituent is O^+. This has been generally accepted on

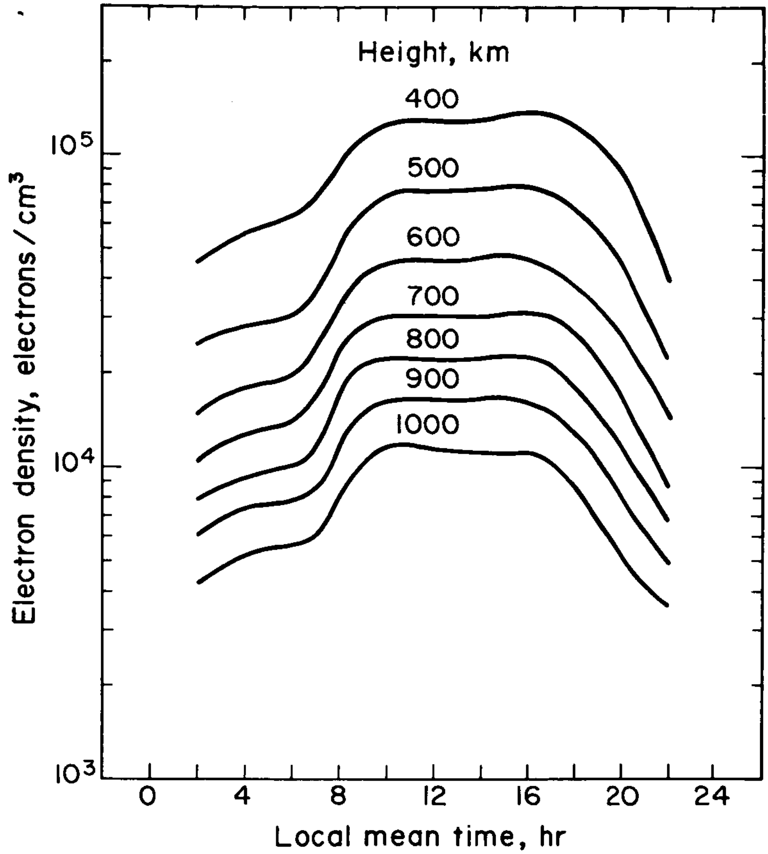

Figure 14.—**Average diurnal variation of electron density at fixed altitudes: 40° N to 45° N, October–December 1962.**

theoretical grounds for many years, but the first direct proof came from a mass spectrometer measurement made in 1958 on Sputnik III by Istomin et al. (ref. 72). At greater heights, O^+ was thought to be gradually replaced by H^+ as principal constituent, via a charge-exchange reaction. In 1961, however, Nicolet (ref. 73) suggested on theoretical grounds that helium was likely to be an important constituent near 1000 kilometers, forming an intermediate layer. The experimental discovery of He^+ as a major constituent was first reported in 1962 by Bourdeau, Whipple, Donley, and Bauer (ref. 74), using an ion trap on Explorer VIII. Independently, Hanson (ref. 75) inferred the same result from a reinterpretation of an ion profile obtained by Hale, on the grounds that a fourfold decrease of mass with altitude was more likely than a fourfold increase in temperature near 1000 kilometers.

Further work has provided some indications of the variability of the altitudes of transition between regions where O^+, He^+, and H^+ are the major constituents. By using the diffusive-electrostatic equilibrium conditions of Mange (ref. 76), together with the appropriate boundary conditions, Bauer (ref. 77) deduced the variation of these transitions with neutral temperature shown in figure 15. Note especially that at low temperatures the helium layer is too thin to be detected from the slopes of electron density profiles. Measurements taken on a number of rocket flights and the Ariel I ion spectrometer seem to agree in general with this theory at medium latitudes, but Bowen, Boyd, Raitt, and Willmore (ref. 78) also find a longitudinal variation (alined with the geomagnetic equator) and an increase in the O^+ concentration with latitude. Their results suggest that the ion composition depends more on magnetic than geographic latitude.

Electron Temperatures

Strong experimental evidence indicates that the electron temperature exceeds the neutral (and ion) temperature by a considerable amount, even at high altitudes, during the day, and by a lesser, but still significant, amount at night. This evidence has come from the direct measurement devices on Explorer VIII (ref. 79), on Ariel I (ref. 80), on Explorer XVII (ref. 81), on Discoverer satellites (ref. 82), and on a number of sounding rockets (ref. 83) and backscatter soundings (ref. 84). There is also some indication that the magnitude of this temperature excess varies con-

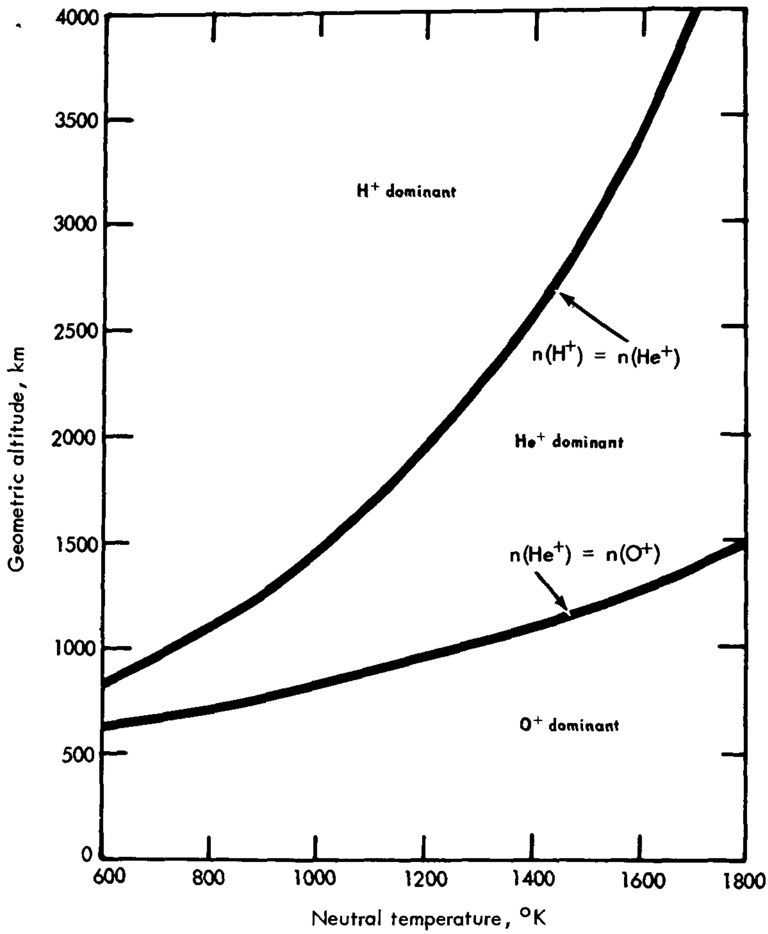

Figure 15.—Transition altitudes between regions where O^+, He^+, and H^+ are dominant constituents, as functions of neutral temperature (theoretical).

siderably with the sunspot cycle. From the same sources, it also appears that the electron temperatures increase with latitude toward the poles and the electron temperature at a fixed altitude shows a rapid rise after sunset, with a maximum before noon and a fairly flat portion after noon. Figure 16 shows some preliminary, smoothed, diurnal

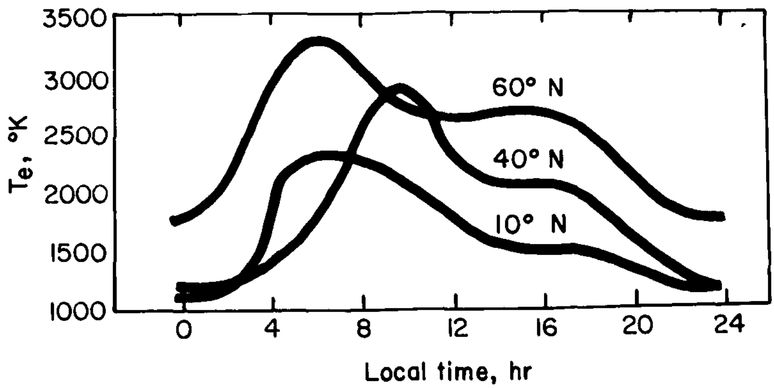

Figure 16.—Diurnal variations of electron temperature for north latitudes of 10°, 40°, and 60° and altitudes in the 260- to 400-kilometer range. Data from Explorer XVII.

temperature variations for three latitudes from Explorer XVII.

The theoretical treatment of charged-particle temperatures above about 300 kilometers is rather difficult, since consideration must be given to all the mechanisms by which photoelectrons can lose their energy, including the energy lost far from the region of the original photoionization. Hanson (ref. 46) and Dalgarno, McElroy, and Moffett (ref. 47) concluded that the electron temperature should approach the gas temperature at high altitudes. Both Bourdeau (ref. 85) and Geisler and Bowhill (ref. 86) have pointed out that these calculations were made for particular conditions of high electron density near sunspot maximum when the electron heat conduction is small. Near sunspot minimum, with lower electron densities, "thermal runaway" is possible, leaving the previously negligible electron heat conduction term the controlling factor in the electron temperature distribution and permitting the electron temperature to exceed the gas temperature at high altitudes. The elevated electron temperatures in the morning and at higher latitudes can be qualitatively understood in terms of the lower prevailing electron densities, since the excess electron temperature over the gas temperature $(T_e—T_g)$ is roughly proportional to Q/N^2, where Q is the heat input and N the electron density.

The energy balance, as evaluated from the neutral- and charged-particle temperatures, has an important bearing on whether there is any significant corpuscular source of ionization or whether solar UV is the dominant source. Both Bourdeau (ref. 85) and Willmore (ref. 87) concluded that the daytime heating can be accounted for by solar UV, but that an additional heat source was required at night, although small compared with the daytime UV source. Geisler and Bowhill (ref. 86) consider that the nighttime heat flow can be maintained by downward conduction from the protonosphere and that this protonospheric heat reservoir is the only significant energy source for the nighttime ionosphere.

THE PROTONOSPHERE AND VLF PHENOMENA

The protonosphere is that part of the Earth's atmosphere in which protons are the main ionized constituent. Figure 15 shows that the lower boundary varies with temperature over the range 1000 to 5000 kilometers. The upper boundary is at the magnetopause, the limit of the Earth's magnetic field, at about 10 Earth radii on the sunlit side. This region is sometimes also called the magnetosphere or exosphere, even though the boundaries are not quite the same.

Since the pioneering work of Storey in 1953 (ref. 88) on whistling atmospherics, or whistlers, the propagation of VLF waves, both natural and manmade, has been used in studying this region. Conversely, such studies have provided the impetus for theoretical work on the propagation of VLF waves in plasmas and the interaction of VLF waves with streams of charged particles. A recent account of the history and modern theory of whistlers and other VLF phenomena has been given by Helliwell (ref. 89).

The impulsive noise generated by a lightning flash enters the protonosphere and is dispersed in frequency. This frequency-dispersed signal, in the form of a gliding tone, or whistler, either on the ground or in space, can provide an integrated measurement of the properties of the medium between the transmitter and receiver. Since the travel time is weighed inversely as the magnetic field in the integral, the dispersive properties are more sensitive to conditions near the top of the path. As discussed by Carpenter and Smith (ref. 90), careful measurement of whistlers observed on the ground enables the vertical electron density profile to be estimated in the equatorial plane, subject to proper identification of the whistler path from the nose frequency and assumptions about the approximate symmetry of the distribution when inverting the dispersion integral. A composite of such results for a variety of conditions is shown in figure 17. Each curve has been obtained as an average of a number of different observations, since one profile cannot be obtained from a single observation. During magnetic storms these electron densities may be reduced by as much as an order of magnitude (Carpenter (ref. 91) and Helliwell, private communication). There is also evidence of a "knee," or rapid decrease in the electron density, at distances of several Earth radii (ref. 90). Direct measurements by Explorer XVIII (IMP I) have confirmed this for the equatorial plane (ref. 92), and measurements on Lunik I, II, and III indicate that the knee moves in close to the Earth at high latitudes (ref. 93) and during magnetic disturbances.

According to Liemohn and Scarf (ref. 94), the high-frequency cutoff of whistlers is below the value expected on simple theory for the electron gyrofrequency at the top of the whistler trajectory, but can be accounted for by Lan-

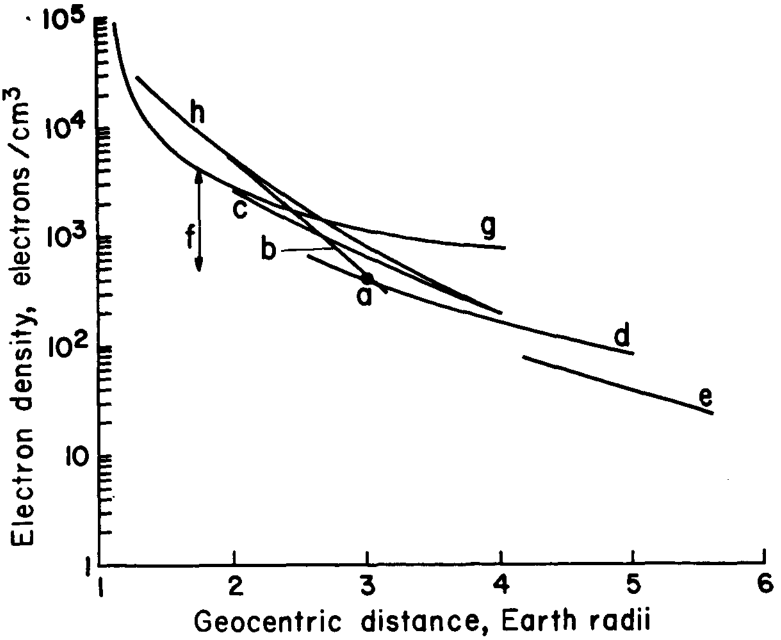

Figure 17.—Experimental equatorial electron density profiles in the protonosphere: (a) Storey, (b) Allcock, (c) Carpenter and Angerami, (d) Smith, (e) Pope, (f) Bowles, (g) Schmelovsky, and (h) Schoute-Vanneck and Muir.

dau damping from the high-energy tail of a non-Maxwellian electron velocity distribution. According to F. S. Johnson (private communication), this damping might be more naturally considered as arising from the low-energy tail of the trapped-particle population.

The theory of the electron distribution in the exosphere has recently been reexamined by Angerami and Thomas (ref. 95). They assumed diffusive equilibrium along field lines, took account of centrifugal force, and used the observed electron density at 1000 kilometers (from Alouette I) as a lower boundary condition. Some results of these computations are shown in figure 18. Good agreement could be obtained with the observations shown in figure 17

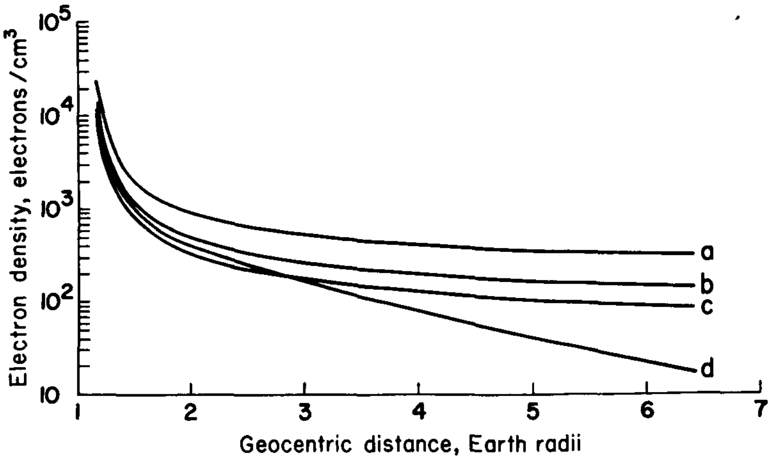

Figure 18.—Equatorial electron density profiles, computed by Angerami and Thomas for $T=1500°$ K (ref. 95). (a) Summer day, (b) winter day, (c) winter night, and (d) summer night.

using summer night data, ion compositions consistent with other measurements, and an isothermal protonosphere. Unlike some earlier theories, a good match could be obtained with the vertical gradient of electron density as well as its magnitude. The lack of success for daytime boundary conditions probably arises partly from the assumption of isothermy, since this is less nearly correct during the day than at night. As the equations are given in general form, however, this work can be extended relatively easily to incorporate the most recent data on electron temperatures.

Vanguard III, in 1959, was the first satellite to receive whistlers and to record fractional-hop whistlers transmitted from the ground to the satellite over a much shorter path than the more usual ground observations. These signals were picked up inadvertently, because the sensing coil of a proton-precession magnetometer, which was connected to a broadband telemetry link, acted as a loop antenna (ref. 96). Since that time, a number of satellites have carried VLF receiving equipment, including Alouette I, Injun III, Lofti I, and OGO I. Observations from satellites enable the whistler path to be more accurately determined and usually have much better signal-to-noise ratios than those made from the ground.

A new phenomenon, the subprotonospheric whistler, has been discovered in a rocket flight and the Alouette I (VLF) records. As described by Carpenter, Dunckel, and Walkup (ref. 97), this type of whistler is characterized by repeated reflection of energy between about 100 and 1000 kilometers. The lower reflection mechanism has long been familiar, but the upper has been explained by Smith (ref. 98) as caused by refraction through a region of transverse propagation by the action of hydrogen ions and a horizontal density gradient.

Another new type of whistler, the proton whistler, has been discovered in Alouette I and Injun III records (ref. 99) immediately following a fractional-hop whistler. The proton whistler consists of an ascending tone that starts at a very low frequency and approaches the proton gyrofrequency asymptotically. The explanation appears to be that a whistler originating at the ground can pass through a coupling region where this additional signal is generated, with a circular polarization of opposite sense to the usual whistler and a longer travel time.

A considerable body of data has been collected on a variety of emissions with dispersion characteristics different from whistlers. Possible mechanisms for generating these from charged-particle interactions have been summarized by Brice (ref. 100). Helliwell (ref. 101) showed that periodic VLF emissions could be triggered by whistlers and that the data are incompatible with a generation mechanism based on particle bunches oscillating between mirror points.

The mechanism for the passage of whistler energy into the ionosphere through the collision-dominated region is not yet fully understood, and more work on this problem is needed. Recent attempts to measure the amplitude and direction of propagation of VLF signals from rockets have led to results not fully in accord with theory (Storey, private communication). The distribution of VLF energy in the protonosphere itself poses interesting problems. Ground-based evidence and, in particular, the multicomponent whistlers examined by the Stanford group have led to the current ideas on propagation along field-alined ducts. Although such ducts are seen at higher frequencies by Alouette I and Explorer XX, there is as yet no direct *in situ* evidence for ducted propagation at VLF. On the contrary, the reception of manmade signals from satellites indicates that propagation is not limited to such ducts, since such signals can be received over very large areas (ref. 102). Direct evidence for the existence of diffuse whistlers not associated with ducts has also been obtained from rocket flights by Cartwright (ref. 103).

chapter 3

Dynamic Effects

ELECTRODYNAMIC DRIFTS

IT HAS FREQUENTLY been suggested that electrodynamic forces play an important role in controlling the undisturbed ionosphere. The gravitational (tidal) and thermal motions of the neutral atmosphere sweep electrons and ions across the Earth's magnetic field, generating a current by dynamo action. This current, flowing at about 100 kilometers, is responsible for the magnetic fluctuations seen on the ground. It is then supposed that the electric fields generated in this region can in turn cause the F-region ionization to move by a motor action. These ideas have been summarized by Ratcliffe and Weekes (ref. 104), who provide an extensive bibliography.

As discussed in previous chapters, a number of the phenomena for which electrodynamic explanations had been devised have now received alternative explanations, and no direct evidence has been found for the motor theory. And yet it seems clear that there should be some such effect. The success of Baker and Martyn (ref. 105) in explaining the high currents observed in the equatorial electrojet by a polarization field which inhibits the flow of Hall current is certainly strong evidence for the existence of polarization fields at heights of the order of 100 kilometers over the magnetic equator. The question still to be resolved is whether the motor effect of such fields on the F-region is a dominant factor or a small perturbation. Measurements of the currents and electric fields are badly needed, but are very difficult to make.

The current at the magnetic equator is much more intense than at higher latitudes and has been measured with rocket-borne magnetometers by Singer, Maple, and Bowen (1951, ref. 106) and Cahill (1959, ref. 107). The results of these and some more recent flights do not entirely agree with theory, as they sometimes indicate a double current sheet and at other times a thick current sheet extending into the lower F-region. The experiment becomes more difficult at midlatitudes, partly because of the smaller current and partly because of the much greater directional discrimination needed. Measurements were made in 1964 at Woomera by Burrows and Hall (ref. 108), who found a current sheet slightly lower and thinner than expected, and by J. N. Davis at Wallops Island (private communication) with somewhat similar results. More experimental work is needed to map the current system, since neither the vertical current distribution nor the magnetic field at zero current can be obtained from ground-based magnetometers.

While the exact nature and magnitude of the contribution of electrodynamic effects to the quiet midlatitude ionosphere are still an open question, there are high-latitude phenomena, particularly those associated with magnetic storms, that more clearly indicate magnetic field effects. Fejer (ref. 109) has shown how auroral electrojet currents similar to those inferred from magnetic measurements may be formed by convective motions in the magnetosphere in which trapped particles participate. Direct verification of this theory awaits simultaneous observations of the trapped particles, the distorted geomagnetic field, and the electric field.

SPORADIC E

Sporadic E is a thin layer of ionization or irregularities found at altitudes near 100 kilometers, with a complicated morphology (ref. 110). Quite probably a number of different phenomena are involved. In midlatitudes, sporadic E has been observed many times from rockets, and these observations have clearly shown that midlatitude sporadic E consists of a very thin intense layer. A number of workers, notably Whitehead (ref. 111), have suggested that sporadic E might be produced by wind shears, which are known to exist from meteor-trail and chemical-release observations. Some corrections of sign are discussed by Hines (ref. 112), and further comments, as well as a more complete set of references, are given by Axford (ref. 113). Measurements made by a number of workers including Rosenberg, Edwards, and Wright (ref. 114) have confirmed that a correlation exists between sporadic E and wind shear, but they sometimes show that the latter has the wrong sign. Figures 19, 20, and 21, courtesy of L. G. Smith, show some recent measurements of electron density and wind structure made from the same rocket on the evening of October 7, 1964, at Wallops Island. The electron density was measured by a Langmuir probe during ascent and the wind structure by releasing trimethyl aluminum (TMA) during descent. The probe saturated in the sporadic E-layer at an electron density an order of magnitude higher than that observed in adjacent layers, and this layer was situated in a region of high horizontal wind gradient. There seems little doubt now of the association between some types of sporadic E and wind shears, although this relationship is not as simple as was supposed at one time. Further work is planned with TMA, since its use enables observations to be made throughout the night; also, the neutral temperature may be obtained at twilight from the aluminum oxide resonance bands.

Near the magnetic equator, sporadic E takes on a different form; as described by Cohen, Bowles, and Calvert (ref. 115), it is closely associated with the electrojet current. Farley (refs. 116 and 117) has shown that a fam-

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ily of longitudinal (acoustic) waves may be set up by a plasma instability associated with the electrojet and driven by a difference between the electron and ion velocities in the electrojet. The detailed radar measurements of echo amplitude, aspect sensitivity, and Doppler shift all support

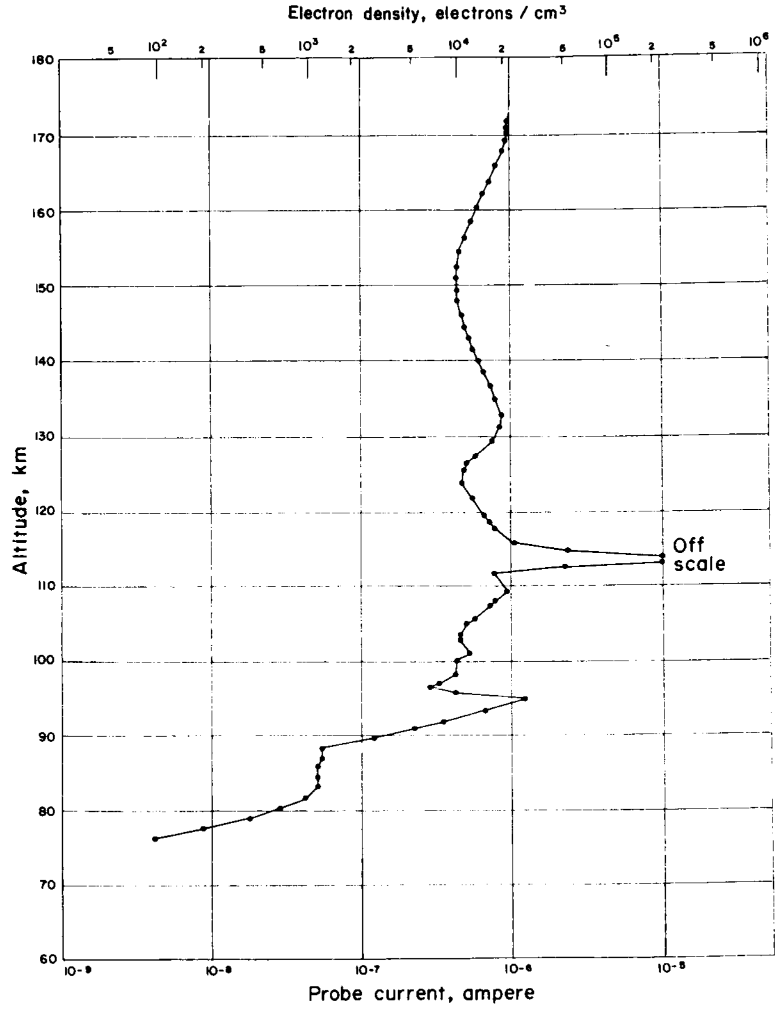

Figure 19.—Electron density from Langmuir probe on Nike-Apache 14.195, October 7, 1964, 18:04 e.s.t., Wallops Island, Va.

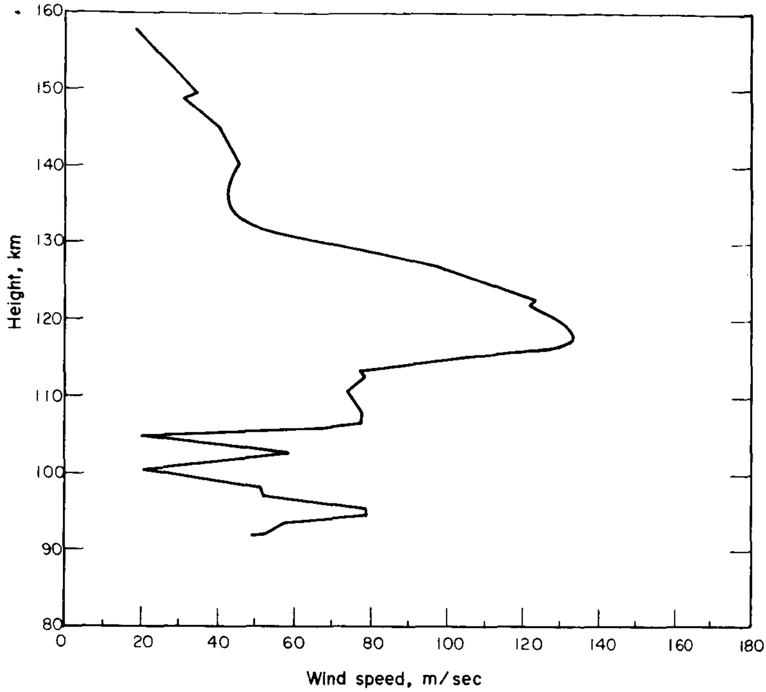

Figure 20.—**Wind speed from trimethyl aluminum release (same flight as fig. 19).**

this explanation (ref. 118) and also suggest that some types of auroral irregularities are produced by a similar mechanism.

IRREGULARITIES AND WINDS

Much effort has gone into investigating ionospheric irregularities and their motions. These are responsible for the fading of radio waves, the scintillation of stellar radio sources, and the fluctuations in the signal strength of satellite transmissions. Irregularities are found at all heights in the ionosphere and in a large range of sizes. Above the F-region electron peak, where the effects of collisions are extremely small, the large-scale irregularities are strongly field alined and can duct radio signals. At low altitudes,

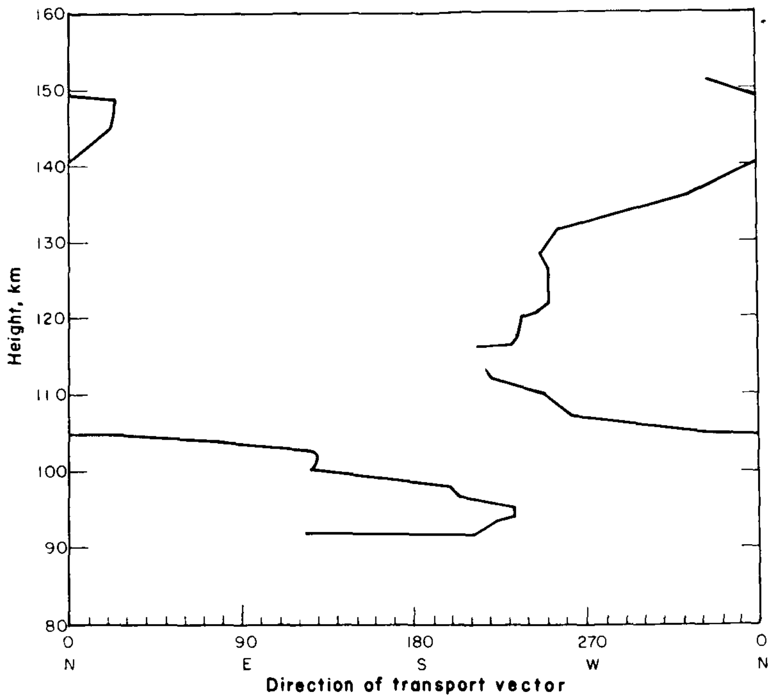

Figure 21.—Wind direction from trimethyl aluminum release (same flight as figs. 19 and 20).

in the collision-dominated region, there is no evidence for field alinement, and at intermediate altitudes there is evidence that blobs of irregularities are elongated in the direction of field lines.

The origin of ionospheric irregularities is still uncertain, although several mechanisms have been postulated and a number of different phenomena appear to be involved. The theory of internal atmospheric gravity waves has been developed by Hines (refs. 119 and 120). These are generated by tidal and wind forces in the lower (neutral) atmosphere, grow in amplitude with height due to the decreasing density, and perturb the plasma in the process. Although this theory seems to account for a number of the observed features, Heisler and Whitehead (ref. 121) report measurements of group and phase velocity on traveling disturbances which disagree with this theory. In addition, the theory apparently cannot account for the latitudinal distribution of irregularities, although this might be explained by a development which includes magnetospheric convection as discussed by Axford and Hines (ref. 122). It has already been mentioned that equatorial sporadic E is thought to arise from a two-stream instability associated with the electrojet, and midlatitude sporadic E from wind shears. Other mechanisms, involving turbulence and hydromagnetic waves, have also been invoked; but thus far theories based on them do not seem firmly grounded.

Irregularities and associated movements may be investigated by observing released chemicals and meteor trails. Radio methods include observation of the scintillation of radio stars and comparison of fading patterns at spaced receivers. These are discussed in detail by Briggs and Spencer (ref. 123). The spaced-receiver method suffers from the disadvantage that the height at which the movements are measured is not clearly established; in the lower ionosphere, where the winds are known to vary rapidly with altitude, this disadvantage can be quite important.

Rocket and satellite techniques have produced a wealth of new data. By observing the fluctuations of satellite signals at several locations, information is obtained about the intensity, size, and altitude of the irregularities in the F-region. Yeh and Swenson (ref. 124) have summarized observations over the past 5 years and provide an extensive bibliography. They report strong diurnal, seasonal, solar-cycle, and latitudinal effects on the occurrence rate of the scintillations. The irregularities were seen at all altitudes, with a peak in the rate of occurrence at about 350 kilometers, at night. The diurnal variation of the altitude distribution at temperate latitudes has been given in more detail by McClure (ref. 125) using Transit 4A observations, and is shown in figure 22. Another manifestation of irregularities is known as Spread F, after the spreading of ionogram traces in the F-region. Calvert and Schmid (ref. 126) have recently examined the Alouette I sounder records for Spread F and report three distinct types. A common form is due to aspect-sensitive scattering from field-alined irregularities. The frequency with which this form was seen on records for the 1962/63 northern winter is shown in figure 23 as a function of both time and geomagnetic latitude. At present, there are no adequate theories to account for these observations.

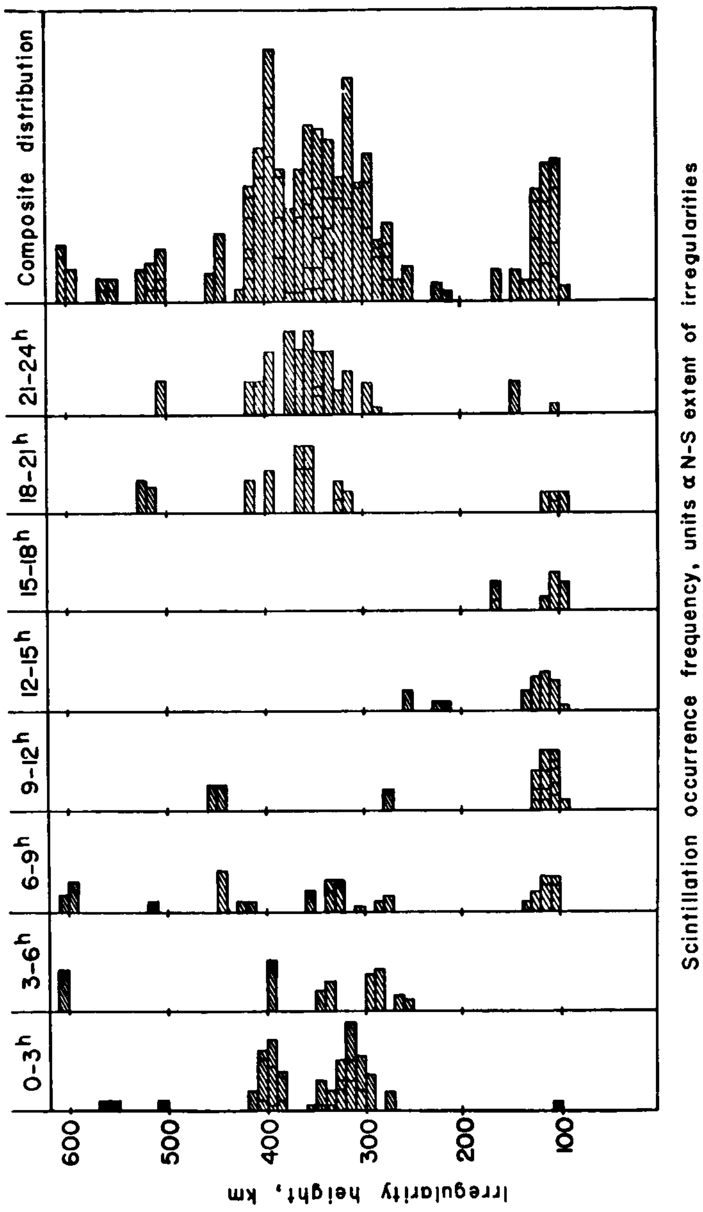

Figure 22.—**Heights of irregularities producing scintillations at different times of day for middle latitudes.**

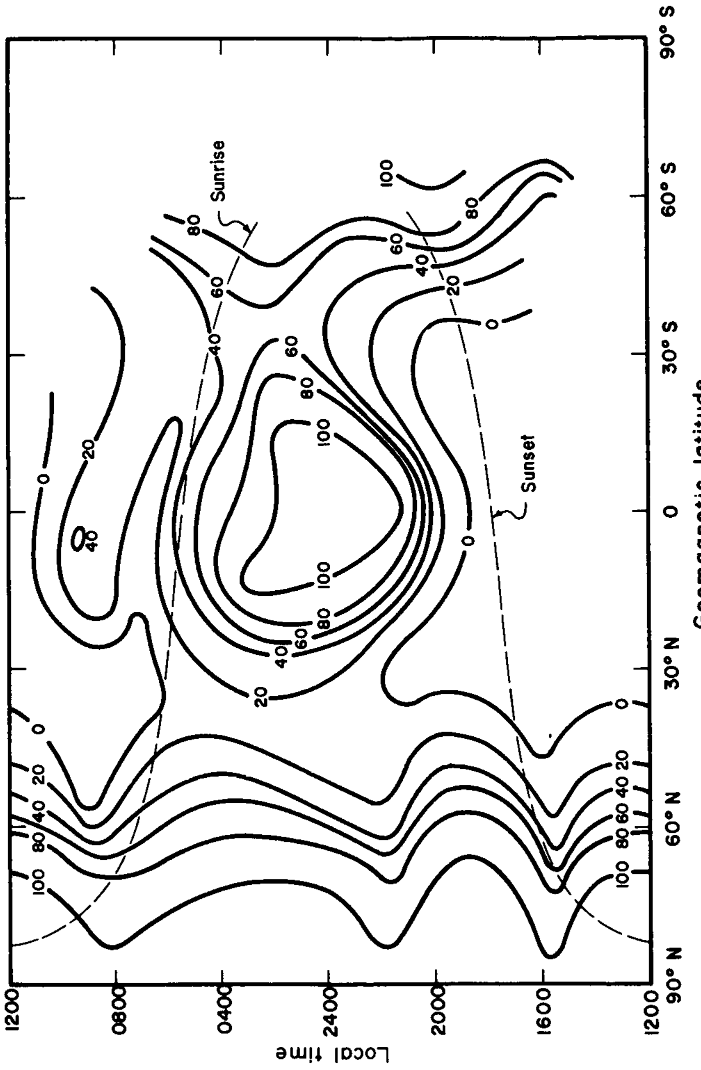

Figure 23.—Occurrence frequency of aspect-sensitive Spread F as seen by Alouette I during the 1962/63 northern winter.

chapter 4

Conclusions and Outlook

GREAT ADVANCES HAVE BEEN MADE in understanding the ionosphere, largely as a result of the information obtained from rockets and satellites. The ground-based incoherent-backscatter technique has also made some contributions and will probably be of increasing value in determining electron and ion temperatures and ion composition, particularly when used with rocket and satellite data.

Data have been obtained from regions previously inaccessible, notably the D-region and the upper part of the F-region, for which a sunspot-minimum morphology is now available in greater detail and with better coverage than for the bottomside. It is hoped to continue this work at least through the next solar maximum. Topside sounders can, in principle, make possible a better use of communications channels by permitting the optimum choice of frequencies based on current conditions measured over large portions of the globe.

Throughout much of the ionosphere, the solar spectral regions responsible for producing ionization have been determined. Less progress has been achieved in determining the mechanisms of electron loss, since many reaction rates are imperfectly known and the role of minor constituents is still uncertain, particularly in the lower ionosphere. More laboratory work is needed on the reaction rates, and improved mass spectrometers are needed to obtain data at the lower altitudes.

It has been shown that electrons in the F-region are produced by a wide range of wavelengths, and that the F2 region is formed where the electron production rates decrease with altitude in a manner more complicated than can be described by a single Chapman function.

New measurements have established that the electron temperature above the E-region generally exceeds the neutral gas temperature, even at night. This temperature excess is dependent on altitude, latitude, and time of day, but has yet to be observed over a solar cycle. It is believed that these results can be accounted for by the known energy-exchange mechanisms between photoelectrons, ions, and neutral molecules.

The detailed diurnal and seasonal variations of electron density at fixed altitudes in the F-region are not properly understood, although some progress has been made in accounting for the morning maximum by incorporating into the theory the diurnal temperature variation of the neutral atmosphere.

Helium was discovered to be an important ionospheric constituent, and theories of diffusive equilibrium have explained the variation with temperature of the altitudes at which oxygen, helium, and hydrogen become the major atmospheric constituents. These theories seem to account for a number of day and night measurements at middle latitudes during different parts of the solar cycle, but not for the recently reported latitudinal variation of helium concentration.

Plasma resonances discovered on topside sounder records have been shown to arise from longitudinal oscillations at the electron gyrofrequency and its harmonics, at the electron plasma frequency, and at an rms combination of these frequencies. Neither the detailed excitation mechanism nor the structures observed have yet been explained. Other VLF resonances have been discovered which arise from multi-ion effects, and new types of whistlers have been observed involving the proton gyrofrequency resonance and a subprotonosphere reflection effect.

Work on irregularities has revealed the statistics of occurrence and the altitude distribution as a function of time, and it has provided some indications of the size of the irregularities. Field-alined ducts have been observed by the topside sounders and shown to be effective in guiding radio energy in the megacycle range.

It has been shown that, at the magnetic equator, sporadic E arises from an acoustic wave generated by a two-stream instability associated with the electrojet. At middle latitudes, sporadic E is a very thin, intense layer of ionization associated with wind shears, but in a more complicated way than described by current theories which occasionally predict the wrong sign for the wind shears.

The maintenance of the polar ionosphere in the absence of solar illumination is not understood. Both ionization by particles and transport of ions from elsewhere have been suggested, but neither possibility has yet been adequately evaluated. Further work is needed on the possible contributions by particles to ionization at high altitudes and high latitudes. In addition, the dynamic effects in the ionosphere, beginning with motions of the neutral atmosphere and continuing with dynamo and motor effects, should be thoroughly examined.

The processes determining the height of the turbopause, where atmospheric mixing ceases and diffusive separation starts, have to be clearly identified, since the turbopause height determines the ratio of constituents at greater altitudes.

A start has been made in measuring the current responsible for quiet-day magnetic variations (the Sq current) at middle latitudes. More measurements are needed to map this current system in detail to relate it to ground-based magnetometer measurements and to electric fields in the ionosphere. Despite some missing details, more is known about the origins and nature of the small short-term variations of the Earth's magnetic field than is known about the main field itself. The study of these details, however, is not merely an example of attempting to learn more and more about less and less, but rather an example of attempting to deduce large-scale behavior from small-scale clues.

The time is ripe for exploration further afield and work has been started on the investigation of low-energy plasma in interplanetary space, in the outer reaches of the solar corona, and in the atmospheres of other planets. Research tools being considered are direct-measurement devices, propagation experiments, planetary-occultation observations, and dropsondes. The recently discovered resonance phenomena may be developed into useful measurement tools. Concurrently, it is vital to maintain theoretical progress in relating these measurements to the physical processes which control the plasma so that the measurements may not only be made, but also interpreted and used to the fullest extent to increase our understanding of the Universe.

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